Quantum Cosmology : An Epistemological and Ontological Perspective on Quantum Cosmology and Levels of the Multiverse

Chapter 1: Introduction

This thesis argues that the many-worlds interpretation of quantum mechanics is unable to derive objective probabilities and the Born rule without falling into circular arguments, and that current cosmological models, such as inflationary or cyclic models, are an epistemologically incomplete view of reality, each presenting its own problems, failing to incorporate quantum gravity and where the block universe hypothesis fails, leading to the emergence of infinities. However, with a quantum cosmology model, and with a universal wavefunction with a closed timelike curve (CTC), and applying the Everett interpretation, all these problems disappear, offering a complete, objective, and ontological view of the universe, giving rise to a spatially finite, edgeless, and seemingly static block universe model, which provides ontological insight into the meaning of the arrow of time and probabilities within the framework of quantum mechanics.

Furthermore, it combines with current theories that attempt to solve the problem of quantum gravity, prioritizing a type of discrete space-time. This "quantum multiverse" model connects with relativistic cosmological models through the Cosmological Multiverse (MWI) hypothesis, applying a holographic method and the principle of complementarity, with both space-time and the Born rule emerging naturally.

I further show that without a theory of hidden variables and superdeterminism, this model is the only way to reconstruct determinism due to the measurement problem. If it is not true, then reality is intrinsically indeterminate, and there is no arrow of time without the appearance of infinities. Only a hidden-variable interpretation could represent a model similar to the one presented here, but it would be inevitably superdeterministic and entail a number of problems that show that Bohm's interpretation is a many-worlds-in-denial interpretation.

Furthermore, both in single-universe models and in cyclic or inflationary models, it is shown that Bohm's interpretation is not able to reproduce the existence of a single possible world, even when the initial conditions during the birth of each universe are the same, whether during a big bounce or the birth of bubble universes or "creation ex nihilo", which is a highly restrictive and unlikely scenario.

Chapter 2 : Levels of the Quantum Multiverse: An

Epistemological and Ontological Perspective

2.1 Re-evaluating the Multiverse: Beyond Tegmark Classification

The notion of a multiverse, a hypothetical set of multiple universes, has gained considerable attention in theoretical physics and cosmology. Although the idea of parallel universes has been contemplated throughout history, it has only been in recent decades, driven by advances in quantum cosmology and string theory, that the concept has acquired a more scientific framework. Max Tegmark proposed an influential classification of multiverses into four distinct levels, each with an increasing diversity of universes [1]. However, the introduction from which this doctoral thesis is developed suggests a novel perspective, presenting a classification of the first three levels of the multiverse as inherently epistemological, related to our way of knowing and observing reality, while the fourth level is conceived as the ontological form of the universe itself.

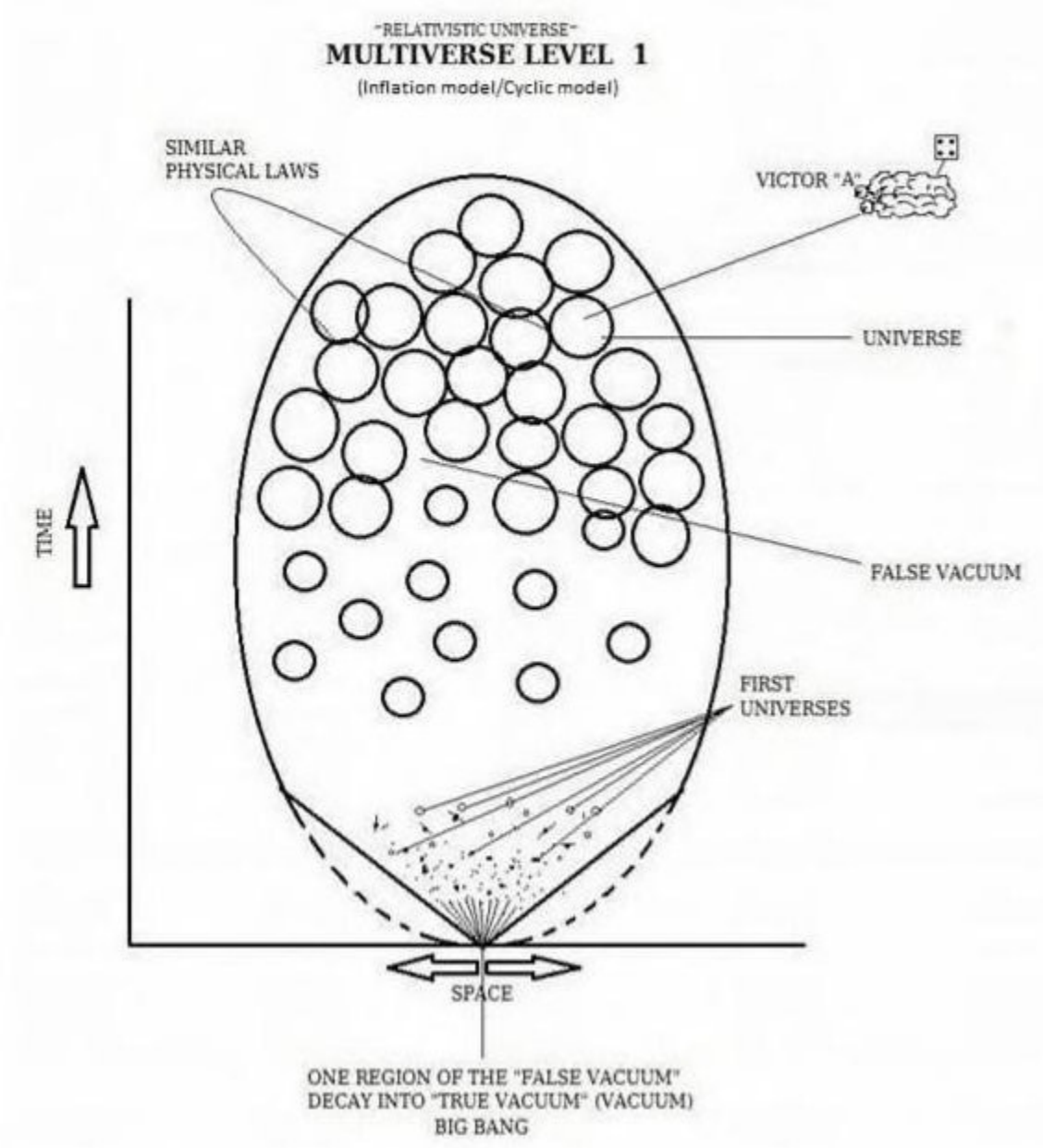
The "01-final quantum cosmology" document [3], while not explicitly detailing these levels of the multiverse, provides crucial context for understanding the quantum cosmology framework on which this classification is based. Quantum cosmology is based on the idea that the principles of quantum mechanics should apply to everything in nature, including the entire universe [3]. This approach attempts to answer open questions in classical physical cosmology, such as those concerning the early stages of the universe. It is important to note, however, that there is still no single, fully defined version of a theory that describes the universe as a quantum system [3].

The distinction between an epistemological and an ontological view of the multiverse is fundamental. Epistemology concerns the nature and scope of knowledge, the justification of beliefs, and the limits of what we can know. Applied to the multiverse, an epistemological level might refer to a perspective or framework within which we understand or access the possibility of other universes, influenced by our observational or interpretive limitations. On the other hand, ontology refers to the study of being or existence. An ontological level of the multiverse would imply the real and fundamental existence of other universes, independent of our ability to directly observe or know them. The proposal that the first three levels are epistemological and the fourth ontological suggests a hierarchy where our initial understanding of the multiverse is tied to our cognitive perspectives and limitations, culminating in a level that represents the ultimate reality of multiple universes.

2.2 Epistemological Levels: Perspectives on Reality

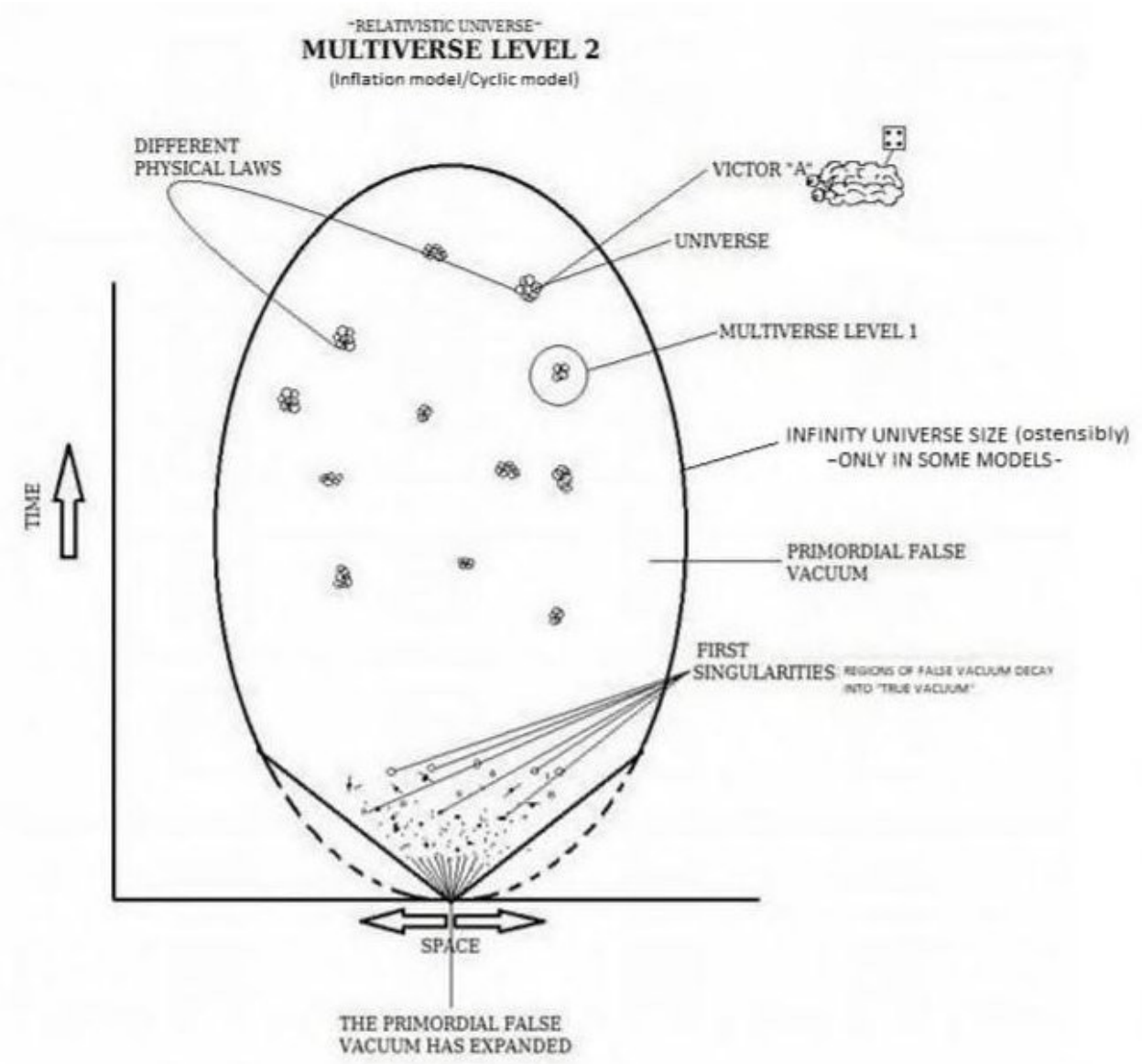
The first three epistemological levels of the multiverse represent different ways in which we can conceive or have knowledge of the existence of other universes, influenced by our limitations and theoretical frameworks.

The first epistemological level might relate to the regions of spacetime that are currently unobservable due to the expansion of the universe and the finite speed of light. The concept of the Hubble volume, which represents everything currently visible from Earth, illustrates this limitation [1]. If space is infinite, as some observations of the cosmic microwave background suggest [5], then there must be an infinite number of Hubble volumes, each with potentially different histories, though obeying the same effective laws of physics [1]. This level resembles Tegmark's Level I, the quilted multiverse, where variations in initial conditions within an infinite universe lead to regions that are copies of our own, but with different distributions of matter [1]. The practical impossibility of interacting with or even observing these regions beyond our cosmic horizon defines their epistemological nature: their existence is a logical consequence of our cosmological theories and observations, but they remain outside our direct empirical reach.



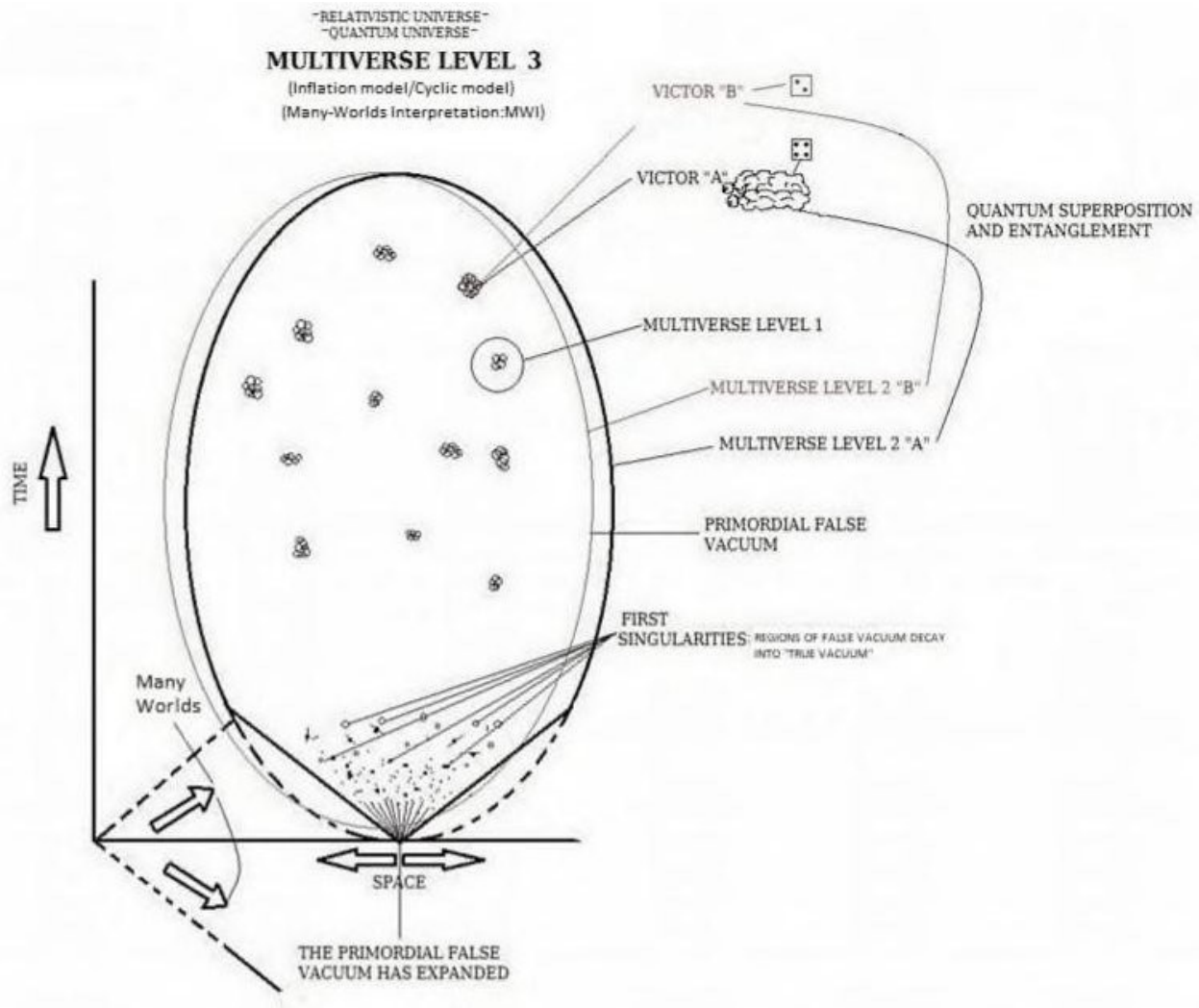
The second epistemological level might concern the possibility of universes with different physical constants or even different laws of physics, as suggested by Tegmark's Level II, the inflationary multiverse [1]. The theory of eternal inflation postulates that during the early inflationary phase of the universe, some regions of space stopped expanding and formed "bubble universes", while other regions continued to inflate [1]. These different bubble universes might have undergone different symmetry breaking, leading to different sets of elementary particles, physical constants, and spacetime dimensionality [7]. Our understanding of these universes is based on theoretical models and extrapolations of our own physical laws. The impossibility of traveling to or even observing these other bubble universes, due to the continuing

inflation of the space between them, places them on an epistemological level: their existence is a prediction of certain cosmological theories, but their specific nature and physical laws are unknown and potentially unknowable to us.



The third epistemological level might arise from the different interpretations of quantum mechanics, particularly the many-worlds interpretation (MWI) [1]. According to the MWI, whenever a quantum event occurs, the universe splits into multiple branches, each representing one of the possible outcomes [1]. These branches or parallel worlds coexist, but do not interact with each other due to the decoherence phenomenon [8]. From an epistemological perspective, the MWI offers us a way to understand the probabilistic nature of quantum mechanics without resorting to the wavefunction collapse postulate [8]. The existence of these “many worlds” is a consequence of taking the wavefunction as

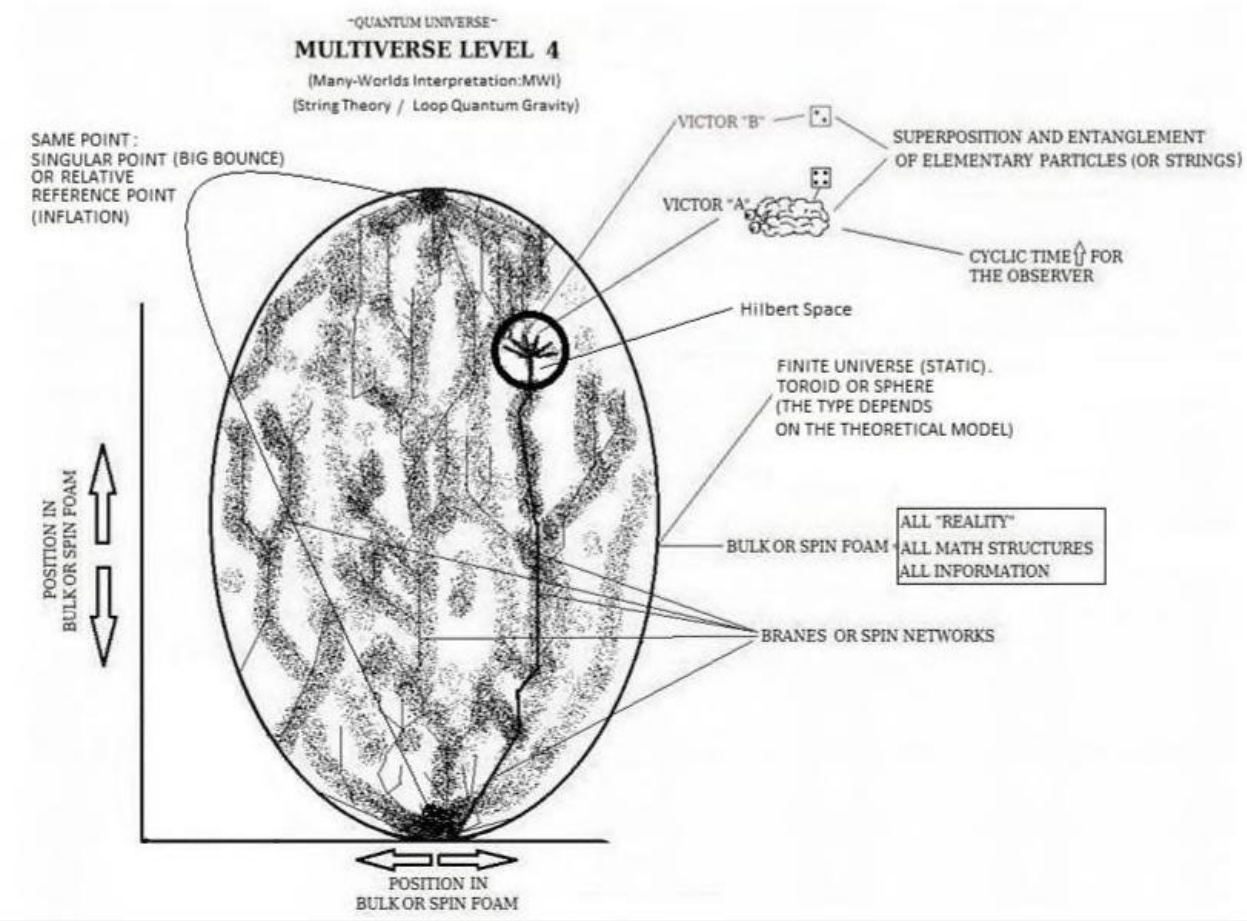
a physically real description of the universe evolving deterministically according to the Schrödinger equation [8] . Our perception of a single outcome is explained by the fact that we are “entangled” with a particular branch of the universe, without having access to the others. This level corresponds to Tegmark's Level III, the quantum multiverse. This level represents a problem of redundant universes where, in Tegmark's model and in the epistemological vision of the present model, the parallel universes of MWI are identical to the universes of Levels I and II, but independent of each other.



2.3 The Ontological Level: The Fundamental Nature of Existence

The fourth level of the multiverse is fundamentally quantum and represents the ontological form of the universe. Unlike previous epistemological levels, which focus on our way of knowing or interpreting reality, this level refers to the fundamental existence of all possible universes arising from a single universal wave function , regardless of our

ability to observe or understand them. The introduction mentions the possibility of discrete spacetime, a concept that has arisen in various quantum gravity theories such as loop quantum gravity [23] and string theory [1], as a possible component of this ontological level.



The idea of a discrete space-time suggests that at very small scales, space and time are not continuous, but are composed of indivisible fundamental units [27]. In loop quantum gravity, for example, space-time is considered to be composed of a finite network of entangled loops called spin lattices, whose time evolution gives rise to spin foams [28]. String theory also involves a fundamental scale, the Planck length, where conventional notions of space and time might cease to hold [40]. A model of quantum cosmology with discrete space-time could provide an ontological basis for the multiverse, where different universes correspond to different configurations or states of these discrete fundamental units.

This ontological level could be related to Tegmark's Level IV, the mathematical universe, which postulates that every consistent mathematical structure also exists physically [1]. If fundamental reality is described by discrete mathematical structures that

give rise to space-time, then different mathematical structures could correspond to different universes with different properties and laws. The ontological nature of this level lies in the assertion that these structures exist as a fundamental reality, regardless of whether we can derive or fully understand them through our epistemological frameworks.

2.4 Contrasting Perspectives: Comparison with Tegmark's Multiverse

The multiverse classification proposed in the introduction differs significantly from Tegmark's four-level scheme in its emphasis on the distinction between the epistemological and the ontological, especially for the first three levels. While Tegmark's levels are primarily based on observational distance and differences in physical laws, the proposed classification focuses on how we know or interpret the possibility of other universes, culminating in a level that represents their fundamental existence.

Tegmark's Level I, the quilted multiverse, where distant regions of space exist with the same physical laws but different histories, could correspond to the first epistemological level of the proposed classification. Both refer to the existence of universes similar to ours, but beyond our observable horizon, the possibility of which arises from the assumption of infinite space and approximately uniform matter distributions. [1] Our inability to directly observe these universes places them in the realm of the epistemological.

Tegmark's Level II, the inflationary multiverse, which postulates universes with different physical constants, could be considered the second epistemological level in the proposed classification. Our understanding of these universes is based on theoretical models and extrapolations, and their unobservability keeps them at a level of knowledge .

Tegmark's Level III, the quantum multiverse based on the many-worlds interpretation of quantum mechanics, aligns closely with the third epistemological level of the proposed classification. Both derive from the idea that each quantum event leads to a splitting of the universe into multiple branches, each representing a different outcome [1] . The epistemological nature in this case lies in the fact that the existence of these parallel worlds is a consequence of a particular interpretation of quantum theory, a way of understanding quantum reality and coupling with each universe of the previous levels . A s noted above, this level represents a problem of redundant universes.

Finally, Tegmark's Level IV, the mathematical universe, where every consistent mathematical structure physically exists, might correspond to the fourth ontological level of the proposed classification. The idea of a discrete spacetime as the fundamental

basis of reality, where different discrete mathematical structures give rise to different universes, aligns with the notion of a fundamental existence that encompasses all consistent mathematical possibilities. The key distinction , however, is that unlike Tegmark's model, which is unclear as to whether his model of Level IV as a mathematical structure is an ontological or epistemological view, at Level IV of his model, the entire universe is ontologically a universal wavefunction, with Levels I and II actually being the same as Level III <MWI=Cosmological Multiverse>, imposing limits on the redundancy of universes while removing the limitations and problems posed by cosmological models and the Everett interpretation alone.

Table 2.1 summarizes this comparison:

Table 2.1: Comparison of Multiverse Classifications

Level	Proposed Model: Description (Epistemological/Ontological)	Tegmark Model: Description	Key Differences
1	Unobservable Regions (Epistemological)	Level I: Quilted Multiverse	Emphasis on observational limitation as the basis for classification in the proposed model.
2	Universes with Different Physical Constants (Epistemological)	Level II: Inflationary Multiverse	It is considered a limitation in our knowledge of the possible physical laws.
3	Quantum Interpretations (Epistemological)	Level III: Many Worlds Interpretation of Quantum Mechanics	The proposed model classifies this as a limited and subjective perspective on quantum reality when coupled to the cosmological universe, where “cosmological multiverse + MWI = redundantly infinite multiverse.”

4	Discrete Space-Time (Ontological)	Level IV: Mathematical Universe	The proposed model specifies a fundamental basis (discrete space-time), while Tegmark's is more general. The proposed model emphasizes fundamental existence, while the previous levels focus on our way of knowing. At this level, the universe displays its ontological form, where "MWI = cosmological multiverse."

This table illustrates how the proposed classification offers a different perspective on the multiverse, based on the distinction between our capacity for knowledge and the fundamental nature of existence, in contrast to Tegmark's classification, which is based more on physical properties and observational distance. The following chapters will explore in detail the foundations of quantum cosmology and the related concepts that underpin this proposed model.

Chapter 3: Fundamental Principles of Quantum Cosmology

3.1 The Quest for Unification: Quantum Mechanics and General Relativity

Quantum cosmology is a branch of theoretical physics whose primary objective is to achieve a unified description of the universe by merging the principles of quantum mechanics and Einstein's theory of general relativity [3] . This endeavor arises from the profound understanding that these two theories, pillars of modern physics, although enormously successful in their respective domains of application, are fundamentally incompatible when applied simultaneously to extreme scenarios, such as the early universe or the interior of black holes. Quantum mechanics, which describes the behavior of matter and energy at atomic and subatomic scales, is based on the quantization of physical properties and the probabilistic nature of phenomena [39] . In contrast, general relativity describes gravity not as a force, but as the curvature of space-time caused by the presence of mass and energy, presenting a deterministic, classical universe on a large scale [38] .

One of the most significant incompatibilities between these theories lies in their treatment of time [4] . In quantum mechanics, time is considered an external classical parameter, an unchanging background against which quantum systems evolve according to the Schrödinger equation [69] . General relativity, on the other hand,

integrates time as the fourth dimension of spacetime, a dynamical entity whose flow rate depends on the curvature of spacetime and the trajectory of the observer [4]. This disparity in the conception of time poses a fundamental challenge to any attempt at unification.

Another major obstacle in the search for a quantum theory of gravity is the renormalization problem [74]. Quantizing gravity using standard quantum field theory techniques leads to the emergence of infinities that cannot be removed by renormalization, a procedure that works successfully for other fundamental forces such as electromagnetism and the weak and strong nuclear forces [39]. This non-renormalizability suggests that general relativity, as currently formulated, might be an effective theory valid only at low energies and that a more fundamental description at higher energies, where quantum effects of gravity become significant, would require a new theoretical framework.

Quantum cosmology stands as the field where this unification becomes particularly crucial. It seeks to apply the principles of quantum mechanics to the universe as a whole, especially at the earliest stages of its existence, near the Big Bang, where quantum effects are thought to have been dominant [3]. Understanding the universe under these extreme conditions requires a theory that can describe the quantum nature of spacetime and matter, overcoming the limitations of general relativity and quantum mechanics when applied separately. Quantum cosmology also aims to address fundamental questions about the origin of the universe, the nature of spacetime at the Planck scale (approximately 10–35 meters), and the ultimate fate of the cosmos [3].

3.2 Key Concepts and Formalisms in Quantum Cosmology

At the heart of quantum cosmology is the idea of describing the quantum state of the universe by a wavefunction, analogous to the wavefunction of a particle in standard quantum mechanics [3]. However, unlike the wavefunction of a particle which evolves in space and time, the wavefunction of the universe is defined in an abstract space of all possible three-dimensional geometries and configurations of matter fields, known as superspace [3]. The equation that this wavefunction is supposed to satisfy is the Wheeler–DeWitt equation, a differential functional equation that arises by applying canonical quantization procedures to the Hamiltonian formulation of general relativity [3].

The Wheeler–DeWitt equation, proposed by John Wheeler and Bryce DeWitt in the 1960s, represents an attempt to quantize gravity by applying the principles of quantum mechanics to the universe as a whole . [3] Unlike the Schrödinger equation, the Wheeler–DeWitt equation does not contain an explicit time parameter, reflecting the timeless nature of general relativity at a fundamental level . [69] Instead, it takes the form of a constraint equation, imposing certain conditions that the wavefunction of the

universe must satisfy. Solutions to this equation would describe the probability amplitudes of finding the universe in a particular configuration of geometry and matter.

The concept of superspace is fundamental to the formulation of quantum cosmology. It is an infinite-dimensional space where each point represents a possible three-dimensional geometry of the universe, along with the configuration of all present matter fields . [3] The wave function of the universe is a functional defined on this superspace, which assigns a probability amplitude to each possible "universe." The evolution of the quantum universe is then described as the motion of this wave function through superspace.

In addition to the Wheeler–DeWitt equation, quantum cosmology also explores the importance of boundary conditions for the universe. In classical cosmology, the initial conditions of the universe must be postulated externally. Quantum cosmology seeks to provide a way to determine these initial conditions from fundamental principles. An influential proposal in this regard is the Hartle–Hawking no-boundary proposal · This proposal suggests that the history of the universe is a compact spacetime manifold with no boundary, analogous to the surface of a sphere. This eliminates the need for an initial singularity and provides a more natural description of the origin of the universe from a quantum state.

3.3 Main Challenges and Open Questions

Despite its ambitious goals, quantum cosmology faces numerous conceptual and technical challenges. One of the most notable is the "time problem" [69] . As mentioned above, the Wheeler-DeWitt equation does not contain an explicit time parameter, making it difficult to describe the temporal evolution of the universe as we observe it. Several solutions to this problem have been proposed, such as identifying an intrinsic variable within the formalism that can act as a clock, or studying semiclassical evolution where time emerges in an approximate manner.

Another important challenge is the problem of the Big Bang singularity [23] . Classical cosmology, based on general relativity, predicts that the universe emerged from a state of infinite density and curvature about 13.8 billion years ago. This singularity represents a point where the laws of physics as we know them cease to apply. Quantum cosmology offers the hope of resolving this singularity by replacing it with smoother quantum behavior, such as a "big bounce" in loop quantum gravity, where a previous contraction phase is followed by an expansion phase [23] .

Interpreting the universe's wave function also presents a significant challenge. Unlike the wave function of a typical quantum system, there is no observer outside the universe who could make measurements and cause the wave function to collapse (if

one adheres to the Copenhagen interpretation). This raises questions about how the universe's wave function relates to the classical reality we observe and whether a different interpretation of quantum mechanics is required in a cosmological context.

Furthermore, quantum cosmology largely lacks direct experimental verification . [26] The energies involved in the early Universe and at the Planck scale are far beyond what we can probe with current experiments. This makes it difficult to test the predictions of quantum cosmology theories and distinguish between different models. However, some researchers hope that quantum effects of gravity may leave subtle imprints on the cosmic microwave background or the large-scale distribution of galaxies, which could be detected with future observations.

Finally, the landscape problem concerns the vast number of possible solutions to the equations of string theory, each corresponding to a universe with different physical constants . [3] This raises the question of why our universe has the constants we observe and whether there is some principle that selects a particular universe from this vast landscape. Quantum cosmology could play a role in understanding the probability of different universes within this landscape.

Chapter 4: The Many-Worlds Measurement and Interpretation Problem

4.1 The Enigma of Measurement in Quantum Mechanics

One of the most puzzling and debated problems in the foundations of quantum mechanics is the measurement problem [19] . Quantum mechanics describes physical systems by a wavefunction that evolves deterministically according to the Schrödinger equation as a linear superposition of different states [19] . However, when a measurement is performed on a quantum system, it is always in a single defined state, rather than in a superposition of all possible states [19] . This transition from a superposition to a definite outcome is known as wavefunction collapse, and the measurement problem lies in describing what exactly causes this collapse and how it happens.

The Schrödinger's cat thought experiment [10] vividly illustrates this problem. In this scenario, a cat is enclosed in a box with a device that will release a poison if a radioactive atom decays. According to quantum mechanics, until the box is opened and the system is observed, the atom is in a superposition of decayed and non-decayed states, and therefore the cat is also in a superposition of alive and dead states [19.] However, upon opening the box, we only find the cat alive or dead, never in a combination of both. The question is, how does the system transition from this indefinite superposition to a single definite outcome? When does the measurement occur? Was it at the moment the cat was observed?

The standard Copenhagen interpretation of quantum mechanics postulates that measurement plays a special role in the theory, causing a non-unitary and irreversible collapse of the quantum state [68]. According to this interpretation, the quantum world is governed by the laws of probability until a measurement is made by a classical observer, at which point the system "chooses" a definite state. However, this interpretation has been criticized for its lack of clarity regarding what exactly constitutes a measurement and the role of the observer [19]. Furthermore, the fundamental division between a quantum system and a classical observer appears ad hoc and is not well defined within the theory.

4.2 The Many Worlds Interpretation: An Alternative Framework

The many-worlds interpretation (MWI), originally proposed by Hugh Everett III in 1957, offers a radical solution to the measurement problem by suggesting that a collapse of the wavefunction never occurs · Instead, the MWI posits that all possible outcomes of a quantum measurement are physically realized, each on a separate branch of the universe · According to this interpretation, the universe evolves deterministically according to the Schrödinger equation, and the act of measurement is simply an interaction between the quantum system and the measuring apparatus (which includes the observer), leading to a superposition state in which all possible histories become real, but in parallel, non-interacting worlds.

The phenomenon of decoherence plays a crucial role in MWI in explaining why we are unaware of these other worlds [8]. Decoherence is the process by which a quantum system interacts with its environment, causing it to lose quantum coherence and behave more classically. In the context of MWI, decoherence causes the universe to branch into distinct worlds that no longer interfere with each other. Each branch contains a defined measurement outcome, and the observer finds himself entangled with one of these branches, perceiving only the corresponding outcome [8].

The MWI has profound implications for our understanding of reality. It suggests that the universe is not unique, but a vast, constantly branching multiverse where all quantum possibilities play out. Each quantum choice or event leads to a split, creating an immense and ever-increasing number of parallel worlds [8]. This interpretation eliminates the need for wavefunction collapse and provides a unitary, deterministic description of the quantum evolution of the universe as a whole [8].

4.3 Challenges and Criticisms of the Many Worlds Interpretation

Despite its elegance and ability to solve the measurement problem, MWI is not without challenges and criticisms [12]. One of the main objections is the preferred basis problem [87]. MWI postulates a branching of the universe into different worlds, but it does not uniquely specify in which basis (i.e., which set of quantum states) this branching occurs.

While decoherence helps to select an "effective" basis for macroscopic objects, it does not provide a preferred fundamental basis at the quantum level.

Another challenge is the difficulty of defining and counting worlds [12]. If every quantum event leads to a split, the number of parallel worlds must be immense, perhaps infinite. This raises questions about the nature of these worlds, their relationship to one another, and whether they are all equally "real." Some critics argue that the proliferation of unobservable universes is an ontological extravagance that violates Occam's razor [87].

A particularly thorny problem for MWI is the derivation of objective probabilities, specifically the Born rule · The Born rule states that the probability of obtaining a particular outcome in a quantum measurement is given by the square of the amplitude of the wavefunction for that outcome. In standard quantum mechanics, this rule is postulated. However, in MWI, where all outcomes occur in different worlds, it is not clear why we should assign probabilities to these outcomes, since they are all true in some world. Furthermore, even if we accept the necessity of probabilities, why should they be given by the Born rule?

Several attempts have been proposed to derive the Born rule within the MWI framework. One approach relies on frequentist arguments, suggesting that in the limit of many measurements, branches that do not obey the Born rule would have an existence measure tending to zero [8]. Another approach uses decision theory, arguing that a rational agent should act as if the Born rule were true in order to maximize their expected utility in quantal bets [8]. Derivations based on self-localized uncertainty [8] and branch counting [8 have also been proposed]. However, these derivations remain controversial and have faced criticism for circularity or relying on additional assumptions [92].

Finally, the MWI faces the so-called "incoherence problem", which asks why we should assign probabilities to outcomes that are certain to occur in some worlds, and the "quantitative problem", which asks why probabilities should be given by the Born [8 rule]. Despite these challenges, the MWI remains one of the most influential and debated interpretations of quantum mechanics, and its relationship to quantum cosmology and the nature of the multiverse continues to be an active area of research.

Chapter 5: Time and Reality: The Block Universe in Quantum Cosmology

5.1 The Block Universe Concept

Block universe theory, also known as eternalism, presents a radical perspective on the nature of time, suggesting that all moments in time (past, present, and future) exist simultaneously within a four-dimensional block of space-time . [71] In this model, time does not flow objectively, and the universe does not change; rather, all events that have

occurred, are occurring, and will occur are equally present within this static block . [71] Our perception of the passage of time and change is considered a psychological illusion, similar to how a movie presents a series of static frames that create the illusion of motion . [71]

This view of time arises naturally from Einstein's theory of special relativity, which treats time as another dimension, on an equal footing with the three spatial dimensions, forming a space-time continuum [4] . Special relativity showed that simultaneity is not absolute, but depends on the observer's frame of reference [72] . What one observer considers "now" may be the past or future for another observer moving at a different relative speed. This relativity of simultaneity suggests that there is no universally defined "present", supporting the idea that all moments in time have the same ontological status [73] .

The block-universe theory contrasts sharply with other conceptions of time, such as presentism, which holds that only the present moment is real, and the past and future do not exist [73] , and growing-block theory, which posits that the past and present exist, but the future has not yet materialized [73] . Whereas presentism is more in line with our everyday intuition of time as flowing, the block-universe theory is seen as a natural outgrowth of the theory of relativity [71] .

The preeminence of the block universe as the central conceptual framework in this thesis is based on its intrinsic coherence with a deterministic universe. In contrast, an indeterministic universe presents serious conceptual difficulties. The inherently random nature of its development entails an arbitrariness and bias that make it difficult to define a well-defined beginning or end to the universe, or even both, with the appearance of infinity. This lack of a predictable and consistent evolutionary trajectory poses significant challenges for its integration with fundamental theories such as general relativity and quantum mechanics.

On the other hand, in the context of a deterministic universe, alternative conceptions of time, such as presentism and growing block theory, face additional challenges. While presentism posits an ontologically privileged present, and growing block theory suggests an existing past and present with a yet-to-be realized future, both perspectives are problematic under strict determinism. In particular, the idea of a deterministic universe that is increasingly blocky faces the limitation imposed by the finite, albeit immense, number of possible states of the universe. Given this finiteness, the sequence of states would inevitably repeat itself at some point, implying a cyclical nature of temporal evolution. This repetition essentially transforms a growing universe into a blocky one, where all moments are interconnected in a predetermined pattern.

In this sense, within a deterministic model, concepts such as presentism and the

growing block can be interpreted as partial or epistemological views of a more fundamental and complete temporal reality: the block universe. From this perspective, all temporal moments—past, present, and future—coexist as equally real entities, a logical consequence of the deterministic nature of physical processes as explored in this thesis.

5.2 Implications for the Nature of Time and Causality

The conception of the universe as a static block has profound implications for our understanding of the nature of time and causality. If all moments exist simultaneously, the notion of the "passage" of time becomes a puzzle. Some philosophers and physicists suggest that our perception of flowing time is simply a function of our consciousness or of the increasing entropy in the universe, which defines a thermodynamic time direction . [71] From this perspective, the past appears fixed to us because we have memories of it, while the future appears uncertain because we have not yet experienced it. In reality, both exist within the space-time block . [109]

The idea of a block universe also raises questions about free will . [72] If the future already exists, predetermined within the block, do we really have the ability to make choices that alter the course of events? Some proponents of the block universe mistakenly argue that free will and determinism can coexist, suggesting that our choices are simply part of the pre-existing structure of the block, even if we are unaware of it . [111] Others argue that the block universe implies a form of fatalism, where all our actions and their outcomes are already fixed.

Causality, the relationship between cause and effect, is also interpreted differently in the context of a block universe [111] . In a traditional view, causes precede effects in time. However, in a block where time does not flow linearly, causality can be seen more as a web of interconnections across space-time. An event at one point in the block can be causally related to events at other points, regardless of their temporal separation in our perception. Some have even explored the possibility of retrocausality, where future events could influence the past, within this framework [126] .

5.3 The Block Universe in Relation to Quantum Cosmology and the Many Worlds Interpretation

The relationship between the block universe and quantum cosmology is complex and depends greatly on the interpretation of quantum mechanics adopted [112] . The probabilistic nature of quantum mechanics, as expressed in the Copenhagen interpretation with its collapse of the wave function, appears to be in tension with the deterministic and static nature of the block universe [108] . If the future is already written in the block, how does one accommodate the randomness inherent in quantum events?

The many-worlds interpretation (MWI) of quantum mechanics, however, seems to fit more naturally with the concept of a block universe [12] . In the MWI, every quantum event leads to a branching of the universe, creating multiple parallel worlds where all possible outcomes are realized [1] . Within the framework of a block universe, these branches could be viewed as different timelines or histories coexisting within the block space-time, creating a block "multiverse" where not only all past, present, and future exist, but also all possible variations of these [113] , resulting in a quantum universe with a closed timelike curve (CTC).

It is interesting to note that Hugh Everett himself, the original proponent of MWI, may not have been entirely in favor of the "many worlds" terminology, perhaps preferring a view of a single quantum world described by a universal wavefunction within a block universe [13.] From this perspective, the different "branches" of the wavefunction might not represent separate universes, but rather different components of a single universal quantum state coexisting within the block of space-time. Decoherence would explain why these components appear classical and do not interact at the macroscopic level.

In short, block universe theory offers a provocative perspective on the nature of time and reality, with profound implications for causality, free will, and our understanding of the universe. Its relationship to quantum cosmology and the many-worlds interpretation suggests a framework where all quantum possibilities could coexist within an eternal block of space-time, although the precise nature of this coexistence and its compatibility with the fundamentally probabilistic nature of quantum mechanics remain matters of debate and research.

Chapter 6: Towards a Quantum Theory of Gravity and Discrete Spacetime

6.1 Main Candidates: Loop Quantum Gravity and String Theory

The search for a quantum theory of gravity, which unifies quantum mechanics with general relativity, has led to the development of several theoretical approaches, with loop quantum gravity (LQG) [23] and string theory [1 being] two of the most prominent candidates [39] .

Loop quantum gravity is an attempt to directly quantize gravity based on Einstein's geometric formulation of general relativity, rather than treating gravity as a particle-mediated force · In LQG, the fabric of space and time is considered to be composed of finite loops entangled in an extremely fine network called a spin lattice . The evolution of a spin lattice in time gives rise to a spin foam. A key feature of LQG is that it postulates that space and time are discrete at the Planck scale (approximately 10–35 meters), meaning that there exist indivisible fundamental units of volume and time · [LQG] is formally

considered to be background-independent, meaning that its equations do not depend on a pre-existing space and [time] . One of the strengths of LQG is its treatment of singularities in general relativity, such as that of the Big Bang, which the theory replaces with a "big bounce" [23] . However, LQG is still under development and lacks direct experimental verification at accessible energies [29] .

String theory, on the other hand, addresses the unification of all fundamental forces, including gravity, by replacing the point particles of particle physics with one-dimensional objects called strings [40] . Different vibration modes of these strings correspond to different particles, including the graviton, the hypothetical particle that would mediate the gravitational force [27] . String theory requires the existence of extra spatial dimensions, typically ten in total, with six of them compactified at very small scales [41] . While string theory has made significant advances in mathematical physics and provided insights into black hole physics and early cosmology [40] , it also faces challenges, including the lack of a complete definition under all circumstances and the existence of a vast "landscape" of possible universes, making it difficult to make specific predictions for our universe [40] . Like LQG, string theory has not yet been experimentally verified at the energies required to probe the string scale (approximately the Planck length) [44] .

6.2 The Concept of Discrete Space-Time in Quantum Gravity

The idea that space and time might not be continuous but discrete at very small scales is a common feature that arises in various approaches to quantum gravity, including LQG and potentially string theory [3] . In a continuous spacetime, one can divide any region of volume into smaller and smaller regions ad infinitum. However, the idea of a discrete spacetime posits that there exists a “smallest possible volume” that is no longer divisible [30] . Similarly, there might be a smallest “unit of time”, a “chronon”, beyond which time cannot be divided further [60] .

In loop quantum gravity, the discretization of spacetime arises naturally from the structure of spin lattices [28] , S_SS150 [31] . The nodes of the spin lattice can be interpreted as volume quanta, and the links as area quanta. The size of these quanta is on the order of the Planck length cubed for volume and the Planck length squared for area [28] . This implies that space itself has a granular structure at this fundamental scale, and that lengths, areas, and volumes are all quantized, taking only discrete values.

While string theory was originally formulated in a continuous space-time background, some research suggests that at the Planck scale, space-time might have an emergent and possibly discrete nature [38] . The holographic principle, which arose from string theory, suggests that information contained in a volume of space can be encoded in a lower-dimensional boundary, which might imply that the dimensionality and continuity of

space-time are illusory at a fundamental level [38].

One of the potential benefits of discrete spacetime is its ability to resolve singularities that appear in general relativity, such as the Big Bang singularity or the singularities inside black holes [33]. If there is a minimum length and a minimum volume, then the density cannot become infinite. In loop quantum gravity, for example, the Big Bang is replaced by a Big Bounce, where the universe transitions from a contracting to an expanding phase, avoiding the singularity [23].

6.3 Integrating Quantum Gravity with a Discrete Space-Time Model

The integration of a quantum theory of gravity with a discrete space-time model in the context of quantum cosmology presents a formidable but potentially fruitful challenge. Both loop quantum gravity and string theory, with their inherent or potential implications for discrete space-time, could be integrated within the framework of quantum cosmology to provide a more fundamental description of the universe at its origins and at the smallest scales.

In loop quantum gravity, the loop quantum cosmology (LQC) formalism has already made significant progress in applying LQG principles to cosmological models [23]. LQC replaces the Big Bang singularity with a Big Bounce and provides a framework for studying the early evolution of the universe with discrete spacetime [23]. The Wheeler–DeWitt equation, in the context of LQC, is replaced by a difference equation reflecting the discrete nature of spacetime.

The integration of string theory with discrete spacetime and quantum cosmology is more complex. While string theory itself does not inherently postulate a discrete spacetime, the holographic principle, a consequence of string theory, suggests that the description of a volume of space can be encoded in a lower-dimensional boundary, which might imply an underlying discrete structure · The AdS/CFT correspondence is a specific example of this, relating a theory of gravity in anti-de Sitter space to a conformal quantum field theory at its boundary · This suggests that gravity and spacetime in the bulk (anti-de Sitter space) might emerge from a quantum theory living at the boundary, which might have a discrete structure.

Furthermore, the introduction mentions the concept of a "quantum space" [147] with discrete properties of time and energy points as a possible alternative. This idea, based on a "Quantum Space Theory of Everything" (ToE), postulates that the universe emerged from an initial singularity that could be a certain structure created by quantum space itself, described as a lossless energy structure outside of time, possibly with a "frozen time-lapse" at each energy point147 · While this is a speculative proposal, it suggests another way in which discretization could play a fundamental role in quantum

cosmology.

Integrating these approaches into a coherent model of quantum cosmology with discrete space-time remains a significant challenge. It requires a deeper understanding of the fundamental nature of space, time, and gravity at the Planck scale, as well as the development of the mathematical and conceptual tools necessary to describe the universe under these extreme conditions. However, the potential of such integration to resolve some of the deepest questions in cosmology and theoretical physics motivates continued research in this area.

Chapter 7: The Holographic and Complementarity Principles in Quantum Gravity and Cosmology

7.1 The Holographic Principle: Information at the Border

The holographic principle [1] is a property of string theories and a putative property of quantum gravity which states that the description of a volume of space can be thought of as encoded in a lower-dimensional boundary of the region, like a light horizon as a gravitational horizon [46] . Originally proposed by Gerard 't Hooft, it was given a precise interpretation in string theory by Leonard Susskind, who combined his ideas with those of 't Hooft and Charles Thorn [46] . Susskind said: "The three-dimensional world of ordinary experience—the universe filled with galaxies, stars, planets, houses, rocks, and people—is a hologram, an image of reality encoded on a distant two-dimensional surface" [46] .

The holographic principle arose from black hole thermodynamics and the Bekenstein limit [46] . The Bekenstein limit conjectures that the maximum entropy in any region scales with the square of the radius, rather than the cube as might be expected [46] . In the case of a black hole, the idea was that the information content of all objects that have fallen into the hole could be contained entirely in the surface fluctuations of the event horizon [46] .

The prime example of holography is the AdS/CFT correspondence [45] . This is a conjectured relationship between two types of physical theories. On the one hand, there are anti-de Sitter (AdS) spaces used in theories of quantum gravity, formulated in terms of string theory or M-theory. On the other hand, there are conformal field theories (CFTs) which are quantum field theories, including theories similar to Yang–Mills theories describing elementary particles [52] . The AdS/CFT correspondence provides a non-perturbative formulation of string theory with certain boundary conditions and is the most successful realization of the holographic principle [52] . It suggests that a theory of gravity in (d+1)-dimensional space is equivalent to a quantum field theory in its d-dimensional boundary [142] .

The holographic principle implies a deep connection between gravity and quantum field theory and suggests that space-time itself might be emergent from quantum information encoded in a boundary [46] .

7.2 The Principle of Complementarity: Wave-Particle Duality at Cosmological Scales?

Bohr's complementarity principle [67] is a fundamental concept in quantum mechanics which holds that certain pairs of complementary properties, such as position and momentum or wave and particle properties, cannot be observed or measured simultaneously in a single experiment [67] . Bohr considered it to be one of the fundamental truths of quantum mechanics that setting up an experiment to measure one quantity of a pair, for example the position of an electron, excludes the possibility of measuring the other, however an understanding of both experiments is necessary to characterize the object under investigation [151] .

While the complementarity principle is traditionally discussed in the context of microscopic systems, its underlying principles concerning the limitations of our observation and the dual nature of reality could offer new insights into cosmology. The idea of a "gravitational complementarity principle" has been explored, suggesting that gravity has complementary dual features: the quantum and classical aspects of gravity are complementary and absolutely separated by the Planck length into Planckian and super-Planckian domains, respectively . In this scenario, Einstein's classical equations would be correct at a fundamental level in the super-Planckian domain, and quantum gravity would be entirely confined to the Planckian domain with a new type of very short-range interaction .

7.3 Emergence of Space-Time and Born's Rule from Holography and Complementarity?

The holographic principle offers a potential framework for understanding the emergence of spacetime [33] from a more fundamental, non-gravitational theory at the boundary. The idea is that the geometry of spacetime in the bulk emerges from quantum degrees of freedom living on the lower-dimensional boundary. The holographic principle states that the entropy of ordinary mass (not just black holes) is also proportional to the surface area, not the volume; that the volume itself is illusory, and the universe is really a hologram that is isomorphic to the information "inscribed" on the surface of its boundary [46] .

It is speculated that the probabilistic nature of quantum mechanics, as encoded in the Born rule [8] , might also be an emergent phenomenon from an underlying deterministic theory in the holographic limit. Several attempts have been made to derive the Born rule within the context of MWI [8] , with some suggesting that it might arise from the quantum entanglement structure in the limit theory [133] .

The principle of complementarity could complement this picture by suggesting that our description of the universe at different scales (quantum vs. classical, gravity vs. non-gravity) requires complementary perspectives that are not simultaneously accessible. The emergence of space-time and the Born rule could be complementary aspects of a more fundamental description of reality, revealing themselves at different limits or under different "experimental configurations" (in a cosmological sense).

In summary, the holographic principle offers a promising framework for understanding the emergence of spacetime and gravity from quantum information, and it is speculated that the Born rule, which describes the probabilistic nature of quantum mechanics, might also emerge from this framework. The complementarity principle could provide additional insight into how different aspects of reality, such as spacetime and quantum probability, relate to each other in a fundamental theory of quantum gravity and cosmology.

Chapter 8: Alternative Interpretations: Bohmian Mechanics and the Quantum Multiverse

8.1 Bohmian Mechanics: A Theory of Hidden Variables

Bohmian mechanics, also known as pilot wave theory or de Broglie–Bohm theory [1], is an interpretation of quantum mechanics that postulates the existence of definite particle trajectories, guided by a wavefunction [160]. In contrast to the Copenhagen interpretation, Bohmian mechanics provides a deterministic description of quantum phenomena without resorting to wavefunction collapse during measurement [160]. In this theory, a system of particles is described both by its wavefunction, which evolves according to the Schrödinger equation, and by the actual positions of the particles, which evolve according to a guiding equation that depends on the wavefunction [160].

Bohmian mechanics solves the measurement problem by postulating that particles always have definite positions, even when they are not observed [160]. The outcome of a quantum measurement is determined by the initial position of the particle and the evolution of the wavefunction of the system, both of which are uniquely determined by the initial conditions. The probabilistic nature that we observe in quantum experiments arises from our ignorance of the precise initial positions of the particles, which are assumed to be distributed according to the probability density given by the square of the amplitude of the wavefunction (the Born rule) [160]. In Bohmian mechanics, the Born rule is not a fundamental postulate, but is shown to arise from a "quantum equilibrium" condition on the initial distribution of particle positions [160].

The motion of particles is governed by the guiding equation, which involves a quantum potential derived from the wave function [160]. This quantum potential is responsible for

quantum effects, such as interference in the double-slit experiment, by influencing the trajectories of particles in a non-classical manner. An important feature of Bohmian mechanics is its explicit nonlocality: the velocity of any particle depends on the wave function of the entire system, which in turn depends on the positions of all other particles, regardless of their separation [160].

8.2 Criticisms of Bohmian Mechanics: Nonlocality and Superdeterminism

Despite its ability to provide a realistic and deterministic interpretation of quantum mechanics, Bohmian mechanics has faced several criticisms [161]. One of the most common objections is its explicit nonlocality [160]. The instantaneous dependence of a particle's velocity on the positions of all other particles in the universe appears to conflict with the principles of special relativity, which states that no information or influence can travel faster than the speed of light [160]. While relativistic formulations of Bohmian mechanics have been proposed [161], they often require the introduction of a privileged foliation of spacetime, which appears to violate Lorentz invariance.

Another criticism focuses on the asymmetry in the treatment of position and momentum. [170] In Bohmian mechanics, position is the fundamental variable that always has a definite value, while momentum is defined secondarily via the wave function. Some argue that this does not treat these conjugate variables equally, which contrasts with the symmetric role they play in the standard formulation of quantum mechanics.

Bohmian mechanics has also been linked to the concept of superdeterminism [126]. Superdeterminism is a potential loophole in Bell's theorem that would allow a local hidden variable theory that reproduces the predictions of quantum mechanics by postulating that choices of measurement setups are not statistically independent of the hidden variables determining the measurement outcomes [173]. While Bohmian mechanics itself is a non-local theory, some have suggested that it might require a form of superdeterminism to be consistent with all quantum phenomena, implying a lack of free will for experimenters in choosing measurement setups [126].

8.3 Bohmian Mechanics and the Proposed Model of the Quantum Multiverse

Bohmian mechanics, with its description of a single world evolving deterministically along a non-local wave function, offers a contrasting and unsatisfactory perspective to the many-worlds interpretation inherent in some multiverse models. While MWI postulates the actual existence of all branches of the wave function as separate universes, Bohmian mechanics adheres to the idea of a single objective reality where particles have definite [trajectories].

However, some have argued that Bohmian mechanics could be considered a "many worlds in negation" theory. [160] In Bohmian mechanics, the wavefunction of the universe

contains information about all possible particle configurations, and the branches of the wavefunction that do not contain the actual configuration of particles still influence the motion of the particles through the quantum potential. These "empty branches" or "empty worlds" [160] do not contain particles, but are part of the universal wavefunction and play a role in the dynamics of the "real" world that contains the particles.

Another significant area of tension for Bohmian mechanics lies in its relationship to modern cosmological theories. Most of today's major theoretical frameworks , such as cyclic cosmology, inflationary cosmology, string theory, and loop quantum gravity (LQG), tend to favor or even imply the existence of a multiverse as a natural consequence of their fundamental principles. Bohmian mechanics, with its commitment to a single objective reality and a single evolving universe, stands as an exception to this dominant tendency. In relation to the proposed model of the quantum multiverse, Bohmian mechanics, with its focus on a single objective reality guided by a wavefunction that encompasses all possibilities, could be aligned with the ontological level raised in this thesis, although in a forced way and not without the absence of problems . The "empty branches" of the wavefunction, encoding other possible quantum histories or outcomes, could not be related to the epistemological levels, not even representing different perspectives or ways in which the universe could have been or could be, although only one of these possibilities is realized with real particles , due to their deterministic and inherently one-world nature.

Furthermore, a fundamental criticism of Bohmian mechanics arises from its apparent difficulty in providing a satisfactory account of the computational power of quantum computing. Unlike the Many-Worlds Interpretation (MWI), which finds a natural explanation for the efficiency of quantum algorithms in superposition and parallel processing of multiple worlds, Bohmian mechanics, being a single-world theory with defined particle trajectories, has difficulty explaining quantum computing power without explicitly invoking the superposition principle as a fundamental ontological element. This raises questions about the ability of Bohmian mechanics to provide a complete description of all aspects of quantum phenomena, including those exploited by quantum computing.

The tension between the nonlocality of Bohmian mechanics and the inherent locality of relativity remains a major challenge for this interpretation. Its ability to provide a deterministic description of quantum phenomena without the measurement problem makes it an impractical but certainly intriguing alternative to the standard interpretation and MWI, offering a unique perspective on the nature of quantum reality and its possible relationship to a multiverse model.

Finally, it is crucial to note a fundamental difference in the treatment of objective probabilities between Bohmian mechanics and the MWI. The Many Worlds

Interpretation is distinguished by its attempt to provide an ontological basis for the probabilities we observe in quantum mechanics, linking them to the existence measure or weight of each branch of the universe. In contrast, Bohmian mechanics, like other interpretations such as the Copenhagen interpretation, generally assumes the validity of the Born rule for obtaining probabilities without offering a fundamental ontological explanation of why quantum probabilities have the values they do. While Bohmian mechanics provides deterministic trajectories for particles, their initial distribution and the shape of the wavefunction that guides them are assumed to conform to the Born rule, thus incorporating probability without explaining its ontological origin intrinsically into the theory.

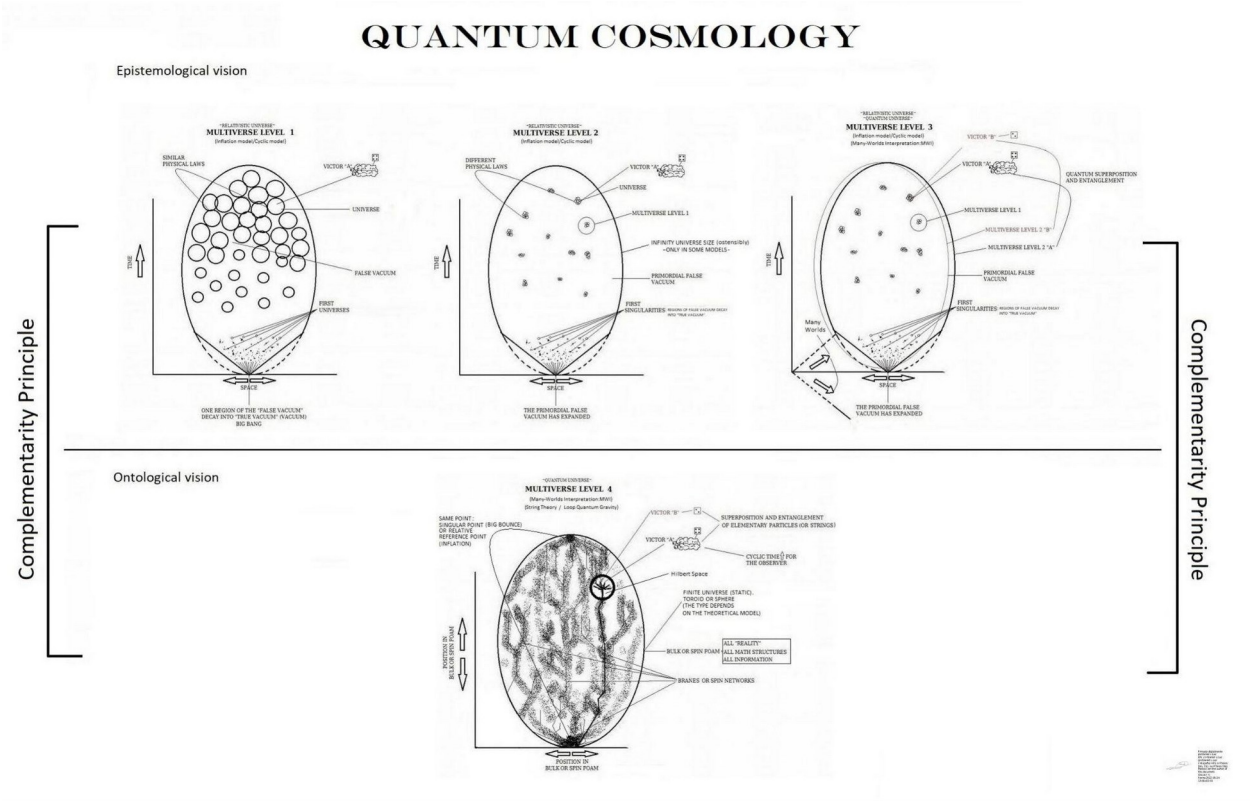
Chapter 9: Synthesis and the Proposed Model of the Quantum Multiverse

9.1 Integrating Perspectives from Quantum Cosmology and Interpretations from Quantum Mechanics

The exploration of quantum cosmology and various interpretations of quantum mechanics reveals a complex and fascinating picture of the fundamental nature of our universe and the possible existence of others. Quantum cosmology strives to unify quantum mechanics and general relativity in order to understand the universe at its beginnings and at the Planck scale, addressing challenges such as the time problem and the Big Bang singularity [3]. The measurement problem in quantum mechanics has given rise to alternative interpretations such as the Many Worlds Interpretation (MWI), which postulates the existence of parallel universes to avoid wavefunction collapse, although this comes with its own challenges related to probability and ontology [1]. Block universe theory presents a view of time as just another dimension, where all moments coexist, which has implications for causality and free will and relates to the MWI in suggesting a block "multiverse" [71]. The search for a quantum theory of gravity has led to approaches such as loop quantum gravity and string theory, which suggest the possibility of a discrete spacetime [1]. Holographic and complementarity principles offer additional insights into the fundamental nature of reality and the possible emergence of quantum spacetime and probability [1]. Finally, Bohmian mechanics presents a deterministic interpretation with non-local hidden variables [1].

9.2 Detailed Presentation of the Proposed Model of the Quantum Multiverse

The quantum multiverse model proposed in this thesis is based on the distinction between epistemological and ontological levels. The first three levels are conceived as epistemological, related to our way of knowing or accessing the possibility of other universes, while the fourth level represents the ontological form of the universe itself.



- **Epistemological Level 1: The Observable Multiverse. This level encompasses regions of space-time that are currently unobservable from our perspective due to the expansion of the universe and the finite speed of light. The existence of these universes is inferred from the assumption of infinite space and approximately** uniform matter distributions .
- **Level 2 : The Parameter Multiverse.** This level considers the possibility of universes with different physical constants or laws of physics, as suggested by the inflationary multiverse. These bubble universes could have arisen from eternal inflation with different symmetry breakings .
- **Epistemological Level 3: The Interpretive Multiverse.** This level arises from the different interpretations of quantum mechanics, particularly the Many Worlds Interpretation (MWI). Each branch of the universal wavefunction represents a parallel universe where a different outcome of a quantum event is realized . [1] The existence of these worlds is a consequence of taking the wavefunction as a physically real description.
- **Ontological Level 4: The Discrete Multiverse.** This level represents the fundamental existence of all possible universes, based on the idea of a discrete space-time at the Planck scale. Different universes correspond to different configurations or states of these discrete fundamental units, possibly governed by different mathematical structures .

The key distinction between the epistemological and ontological levels is that the former refers to our ability to know or infer the existence of other universes through observation and theory, while the fourth level postulates their fundamental existence as an inherent property of reality at the deepest scale.

9.3 Key Features, Implications, and Potential for Future Research

The proposed model of the quantum multiverse offers a new perspective by classifying levels based on their epistemological or ontological nature. It suggests that our initial understanding of the multiverse is intrinsically tied to our observational and interpretive limitations, culminating in an ontological level that represents the fundamental reality of existence. This model could help clarify the different ways in which the concept of the multiverse is discussed and provide a framework for future research in quantum cosmology and related theories.

The implications of this model are broad. It suggests that the probabilistic nature of quantum mechanics, as addressed at the third epistemological level (MWI), could be an emergent property of a more fundamental and deterministic reality at the ontological level (Level 4). The idea of discrete space-time as the basis of Level 4 could have profound consequences for our understanding of gravity, singularities, and the very structure of the universe.

Future research could focus on developing a more detailed mathematical framework for describing ontological Level 4, exploring different models of discrete spacetime and their relationship to quantum gravity theories such as LQG and string theory. It would also be valuable to investigate how the holographic and complementarity principles might provide a connection between the epistemological and ontological levels of the proposed model, perhaps suggesting that our perception of continuous spacetime and quantum probability emerges from a fundamental discrete reality. Furthermore, exploring the philosophical implications of this model, particularly regarding the nature of reality, consciousness, and the interpretation of quantum mechanics, could be a fruitful area for future research.

Chapter 10: Conclusion

This doctoral thesis explores the concept of the universe at a fundamental level from a novel perspective, distinguishing between epistemological levels, related to our way of knowing and observing reality, and an ontological level, which represents the quantum nature of existence. By critically analyzing Tegmark's classification of multiverses and contrasting it with the proposed model, the importance of considering the limitations of our knowledge and the different theoretical interpretations when addressing the possibility of other universes has been highlighted.

Research has delved into the fundamental principles of quantum cosmology, highlighting the search for a unified theory that combines quantum mechanics and general relativity, as well as the challenges inherent in this endeavor, such as the problem of time and the singularity of the Big Bang. Exploration of the measurement problem in quantum mechanics and detailed analysis of the Many Worlds Interpretation have revealed the complexities and profound implications of this interpretation for our understanding of reality and probability.

The concept of the block universe has been examined in its relationship to quantum cosmology and the MWI, suggesting a framework where all possible quantum histories could coexist within an eternal spacetime block. The thesis also addressed current theories of quantum gravity, such as loop quantum gravity and string theory, and how they could be integrated into a model of quantum cosmology with discrete spacetime, which is proposed as the ontological basis of the multiverse in the presented model.

Finally, research has explored the holographic and complementarity principles in the context of cosmology and quantum gravity, suggesting possible avenues for the emergence of spacetime and the Born rule from a more fundamental description. Comparison with Bohm's interpretation as a hidden-variable theory has provided an alternative perspective on the nature of quantum reality and its possible relationship to a multiverse model.

In conclusion, this thesis has developed a detailed framework for understanding the quantum multiverse, integrating concepts from quantum cosmology, interpretations of quantum mechanics, and theories of gravity. The proposed model, with its distinction between epistemological levels and an ontological level based on discrete space-time, offers a new perspective on the nature of the multiverse and opens avenues for future research in this fascinating and fundamental field of theoretical physics.